

CHROMOSPHERES OF CORONAL STARS

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Abstract. We summarize the main results obtained from the analysis of ultraviolet emission line profiles of coronal late-type stars observed with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope. The excellent GHRS spectra provide new information on magnetohydrodynamic phenomena in the chromospheres and transition regions of these stars. One exciting new result is the discovery of broad components in the transition region lines of active stars that we believe provide evidence for microflare heating in these stars.

1. Introduction

Solar and stellar coronae are now observed routinely in X-rays with the Yohkoh, ROSAT, and ASCA satellites and at radio wavelengths with the VLA and other radio telescopes. These data provide our main source of information concerning coronal structure, dynamics, and heating rates, which are controlled by locally strong magnetic fields. High-resolution ultraviolet spectra provide complementary information on the dynamics and energetics of plasmas at lower temperatures in a stellar chromosphere and transition region where the structure, dynamics, and heating are controlled by strong magnetic fields that are connected to the coronal fields. As a result, the combination of X-ray fluxes and high-resolution UV spectroscopy can provide a more complete picture of magnetodynamic phenomena in the atmospheres of the Sun and stars than is provided by the X-ray and radio data alone. In this paper we summarize the new results concerning magnetodynamic phenomena in late-type stars with coronae that have emerged from the analysis of spectra obtained with the Hubble Space Telescope (HST).

Since 1991 we have been observing late-type stars and RS CVn-type

binary systems with the Goddard High Resolution Spectrograph (GHRS) on HST. The GHRS can obtain UV spectra with low ($R = \lambda/\Delta\lambda = 2000$), moderate ($R = 20,000$), and high ($R = 90,000$) resolutions. (See Brandt *et al.* 1994 for a description of the GHRS.) Prior to the installation of the COSTAR optics to correct for the spherical aberration of the primary mirror in December 1993, the spectral resolutions of these modes were somewhat degraded when using the Large Science Aperture (LSA) but not appreciably degraded when using the Small Science Aperture (SSA). We will report here on the analysis of GHRS spectra of 9 stars, including two A-F stars (Altair = α Aql and Procyon = α CMi), three G-K stars (β Dra, α Cen A, and α Cen B), two M dwarfs (AU Mic and VB10), and two RS CVn-type binary systems (Capella = α Aur and HR 1099 = V711 Tau). The spectral types and references to the data analysis papers are listed in Table 1. This is not a complete list of all GHRS observations of late-type stars, but these 9 stars, which are known to have coronae, provide examples of important phenomena across the H-R diagram, and the analysis of the data from most of these stars is now either published or in press.

TABLE 1. Active Late-type Stars Observed with HST/GHRS

Star	Spectral Type	Comments	Reference
Altair	A7 IV-V	Hottest active star	Walter <i>et al.</i> (1995) Simon <i>et al.</i> (1994)
Procyon	F5 IV-V	Inactive F star	Wood <i>et al.</i> (1995)
β Dra	G2 Ib-II	Active supergiant	Obs. 1995 Apr 29
α Cen A	G2 V	Old star	Obs. 1995 May 1
α Cen B	K1 V	Old star	Obs. 1995 May 5
AU Mic	dM0e	Very active dMe star	Linsky & Wood (1994) Maran <i>et al.</i> (1994)
VB10	M8 Ve	End of main seq.	Linsky <i>et al.</i> (1995a)
Capella	G8 III + G1 III	Long Per. RS CVn	Linsky <i>et al.</i> (1995b)
HR 1099	K1 IV + G5 IV	RS CVn	Wood <i>et al.</i> (1995)

We have obtained data for these stars at all three spectral resolutions to address different objectives. The lowest-resolution mode (grating G140L) provides line fluxes in the 1150–1700 Å region suitable for emission measure analyses, estimates of the radiative loss rates from the chromosphere and transition region, and studies of whether photospheric or coronal abundances better characterize the plasma in the transition region. The medium-resolution modes (gratings G140M, G160M, G200M, and G270M) provide

sufficient resolution (typically 15 km s^{-1}) to separate close blends, measure line shifts, and measure line profile shapes quite accurately. Most of the results described later in the paper are based upon the analysis of these data. Finally, the highest-resolution data (typically 3.5 km s^{-1}) are obtained with the two echelle gratings (echelle-A and echelle-B). Because the throughput is relatively low and the simultaneous spectral range small for the echelle modes, so far we have obtained spectra only for the Lyman- α and Mg II h and k lines. These data will be discussed elsewhere. We now describe 7 important new results obtained from GHRS data that are likely magnetodynamic in origin and thus relevant to the main thrust of this meeting. We start with phenomena that can be studied with low spectral resolution and proceed to phenomena that require moderate or high spectral resolution.

2. The Hottest Stars with Transition Region Plasmas

X-ray surveys with *Einstein* and ROSAT have identified Altair (A7 IV-V; $T_{\text{eff}} = 8000 \text{ K}$) as the hottest star with a solar-type corona. The hot OB and chemically peculiar B-type stars are also bright X-ray sources, but shocks in their winds likely play a major role in heating their coronae, and these stars are not generally deemed to be solar-like. Why coronae are not present in the hotter A-type stars is not known, but it is commonly thought to be a result of their thin convective zones. Chromospheric Mg II and Lyman- α emissions have been detected from Altair, but the bright photospheric emission from this star in the UV has made it extremely difficult to observe transition-region lines against this bright background. The high S/N and low scattered-light background of the GHRS makes it feasible to search for transition-region emission lines in such stars. Simon *et al.* (1994) and Walter *et al.* (1995) detected emission of the C II 1334, 1335 Å doublet, the former by subtracting the spectrum of the less active A7 IV-V star 80 UMa and the latter by using spectral synthesis to determine and subtract the underlying photospheric spectrum. Thus transition regions and the nonradiative heating required to balance their radiative losses exist in stars at least as hot as $T_{\text{eff}} = 8000 \text{ K}$ ($B-V = 0.22$). The most important and unexpected result presented by Walter *et al.* (1995) is that the bulk of the C II emission cannot be explained by acoustic heating (by extrapolation of the basal flux from the early-F stars), but rather requires an additional heating source that must be magnetic in character.

3. Flaring on a Very Low Mass M Dwarf Star

Flares, the topic of many papers at this conference, are arguably the most intensely studied solar magnetodynamic phenomenon. Flares are also observed at radio, optical, UV, and X-ray wavelengths from a variety of late-

type stars with luminosities that can exceed 10^{32} ergs s⁻¹ (see review papers by Butler, Byrne, Haisch, and Houdebine in these Proceedings). GHRS spectra added a new component to this study when Linsky *et al.* (1995a) detected a flare on one of the lowest-mass stars known—VB10. This star, which is also called Gl 752B, has been classified as an M8 Ve star with $T_{\text{eff}} = 2600$ K and mass about 9% of solar. It thus lies at the very end of the hydrogen-burning main sequence and is very nearly a brown dwarf. Linsky *et al.* (1995a) observed VB10 with the low-dispersion G140L grating on the GHRS for about 1 hour and detected no emission, except for the last 5 minutes when bright emission lines of C II, Si IV, and C IV were clearly present. The peak enhancement of the C IV emission was at least a factor of 40 over quiescent, and the flare luminosity of the transition region and coronal gas was estimated to be about 4×10^{31} ergs s⁻¹. The existence of flares on very late M dwarfs, which have fully convective interior structures, requires a dynamo different from the $\alpha\Omega$ -type dynamo thought to operate near the boundary of the radiative core and convective envelope of the Sun (e.g., Parker 1993). Concepts for alternative dynamos have been proposed (e.g., Durney *et al.* 1993), and the VB10 flare data should stimulate the development of quantitative models for such dynamos.

4. The Fe XXI 1354 Å Coronal Emission Line in dMe Stars

Maran *et al.* (1994) identified the Fe XXI 1354 Å line in their medium-resolution (grating G160M) spectrum of the very active dM0e star AU Mic. This line, formed in coronal plasma at 1×10^7 K, is often detected during solar flares, but it had not yet been detected reliably in other stars because of blending with a nearby C I line. To our knowledge no other coronal line has been detected in stellar UV spectra, although the lower-resolution EUVE spectra contain many coronal lines at wavelengths below 400 Å. The detection for the first time of a coronal emission line at moderate spectral resolution allows one to determine both random and systematic motions. The AU Mic line profile displayed no significant bulk motion or profile asymmetry, which indicates that the emission was primarily from static plasma, perhaps located in closed field regions rather than in expanding open field regions. Maran *et al.* (1994) derived an upper limit of 38 km s⁻¹ for the turbulent motions of the 1×10^7 K plasma. The emission measure corresponding to the Fe XXI line flux is consistent with the stellar X-ray flux observed by the EXOSAT satellite.

5. Electron Densities in Stellar Transition Regions

The integrated fluxes of collisionally excited transition region lines can be used to infer the plasma emission measure $EM = \int_{\Delta T} n_e^2 dV$ near the tem-

perature where an ion is formed, and the fluxes of lines formed over a broad temperature range can be used to determine the emission measure distribution $EM(T)$. Applications of emission measure analysis to the transition regions of the Sun and late-type stars can be found in Jordan & Brown (1981) and Jordan *et al.* (1987), but there may be difficulties with the standard methods (cf. Judge *et al.* 1995). To proceed from the empirical emission measure distribution to an atmospheric model, which is the run of temperature with pressure or height, requires an independent measurement of electron densities. Fortunately, flux ratios of intersystem lines within multiplets or flux ratios of intersystem lines to permitted lines of the same ion or ions formed at the same temperature are often density dependent. This is because the upper levels of the transitions are depopulated to different extents by collisions and radiation. For such types of line ratios there will typically be a range of n_e for which one line is depopulated primarily by collisions and the other line primarily by radiation. In this range the line ratio is density sensitive, but outside of the range it is not because both lines are depopulated by either collisions (the high-density limit) or radiation (the low-density limit). Intersystem lines or multiplets that can provide useful density-sensitive line ratios include the C II] 2325 Å, O III] 1660 Å, and O IV] 1400 Å multiplets and the Si III] 1892 Å, C III] 1909 Å, N IV] 1486 Å, and O V] 1218 Å lines. For a review of this topic, see Mason & Monsignori Fossi (1994) and Brage, Judge, & Brekke (1995).

Intersystem lines, unfortunately, tend to be weak, and in F- and G-type stars the Si III] and C III] lines are swamped by the bright photospheric spectrum. Perhaps the most useful density-sensitive lines are the four lines that constitute the O IV] 1400 Å multiplet, because these lines are reasonably bright, line ratios within the multiplet are not sensitive to the abundances or ionization uncertainties, and Cook *et al.* (1995) have computed theoretical line ratios that are consistent with solar observations. We have now obtained values of n_e in the transition regions of five stars (β Dra, the G1 III star in Capella, the K1 IV star in HR 1099, Procyon, and α Cen B). We were surprised when our preliminary analysis showed that the electron densities in all of these stars are very similar, $n_e \approx 1 \times 10^{10} \text{ cm}^{-3}$, even though the stars differ greatly in activity and luminosity. Deeper observations of more stars are needed to confirm this preliminary result. For the Capella system, Linsky *et al.* (1995b) were able to use the different stellar radial velocities to show that the intersystem lines are formed mainly in the transition region of the G1 III star and thus are useful in determining the electron densities and atmospheric model for this star.

6. Redshifts of Chromospheric and Transition-Region Lines

The centroid velocities of spatially averaged solar UV emission lines are known to be redshifted, with redshifts in quiet regions increasing systematically from near 0 km s^{-1} for chromospheric lines to about 10 km s^{-1} for lines formed at $T \approx 1.35 \times 10^5 \text{ K}$ (e.g., Doschek *et al.* 1976). At higher temperatures the redshifts decrease rapidly, but this result is uncertain because of possible errors in the laboratory wavelengths (e.g., Achour *et al.* 1995). Ayres *et al.* (1988) and others have discovered a similar trend in the redshifts of active stars observed with IUE. Although there is no generally accepted physical explanation for these redshifts, the enhancement of the redshift velocities in solar active regions relative to quiet regions suggests that the spatially averaged emission is dominated by downflows in magnetic flux tubes.

With the GHRS one can obtain more precise values for redshifts in a broader range of stars. Wood *et al.* (1995), for example, find for the inactive star Procyon a steady increase in redshift with temperature, reaching 11 km s^{-1} in the O V] 1218 Å line formed at $2.5 \times 10^5 \text{ K}$. This trend, which is very similar to that seen in the quiet Sun, is also observed in spectra of the inactive dwarfs α Cen A and B. The active G1 III star in the Capella system shows redshifts in the C IV lines of about 19 km s^{-1} (Linsky *et al.* 1995b). At comparable temperatures, the redshift velocities of the active G1 III star in Capella are approximately doubled compared to those of the quiet stars; this velocity difference is very similar to that between active and quiet regions on the Sun. This finding strengthens the case for an intimate connection of redshifts with magnetic fields. However, the very active dMe star AU Mic shows only a very small redshift (about 3 km s^{-1}) in the C IV lines (Linsky & Wood 1994) and the very active K1 IV star in HR 1099 also shows small redshifts (about 5 km s^{-1}) in the C IV lines (Wood *et al.* 1995). Observations of a broader range of stars are needed to identify trends with magnetic field strengths and coverage factors to better understand the physical processes responsible for the redshifts.

7. Excess Blue Emission in Procyon's Transition Region Lines

Wood *et al.* (1995) fitted Gaussians to Procyon's transition-region line profiles obtained with moderate spectral resolution and very high signal/noise (S/N). They were surprised to find that the C IV, Si IV, and O V] lines show excess emission on the blue side of the line profiles centered near -90 km s^{-1} . There is as yet no explanation for this phenomenon.

8. Broad Profiles: A New Diagnostic of Microflare Heating

Linsky & Wood (1994) used the GHRS to obtain the first moderate resolution profiles with high-S/N of transition-region lines in a dMe star when they observed the C IV and Si IV lines in AU Mic. For data obtained at times when the star was not obviously flaring, they could not fit the line profiles with single Gaussians. Instead, they obtained good fits to the line profiles by using two Gaussians—a narrow Gaussian with $\text{FWHM} \approx 29 \text{ km s}^{-1}$ and a broad Gaussian with $\text{FWHM} \approx 173 \text{ km s}^{-1}$. The narrow Gaussians have similar widths to what is observed in solar quiet and active regions, whereas the broad Gaussians have similar widths to what is observed during solar transition-region explosive events (e.g., Dere *et al.* 1989). Cook (1991) argued that these explosive event profiles, which are observed in regions of complex and changing magnetic fields, are broadened by the plasma turbulence generated by microflares.

On the Sun, the broad components are responsible for about 5% of the total C IV and Si IV emission, but on AU Mic this contribution is 40%. A similarly large contribution is observed for the active star in Capella, and for the very active K1 IV star in HR 1099 the broad component contributes 60% of the total line flux. On the other hand, the inactive stars α Cen A

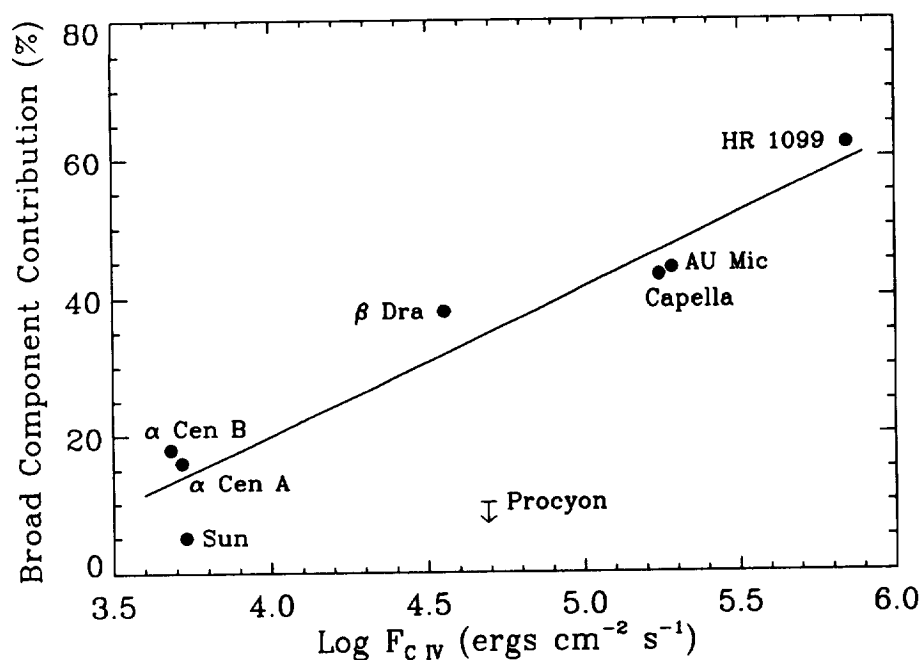


Figure 1. Percentage contribution of the broad component to the total flux in the C IV and Si IV lines is compared with the C IV and Si IV surface flux.

and B and Procyon show either small flux contributions or low upper limits for the broad components. We plot in Figure 1 our preliminary data on the fractional contribution of the broad component to the total C IV and Si IV flux vs. the C IV and Si IV surface flux, a good proxy for the transition-region heating rate. We find a better correlation when we plot the fractional contribution of the broad component vs. the X-ray surface flux, a good proxy for the coronal heating rate, because the Procyon data point then fits the correlation better. This preliminary analysis leads us to conclude that microflaring is the dominant heating mechanism in active stars, but that it plays only a minor role in quiescent stars like the Sun. We will publish our detailed analysis of this new data set elsewhere.

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